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INTERFEROMETRIC ENDPOINT DETECTION
IN A SUBSTRATE ETCHING PROCESS

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INTERFEROMETRIC ENDPOINT DETECTION
IN A SUBSTRATE ETCHING PROCESS

5   **BACKGROUND**

The present invention relates to the detection of an endpoint in the etching of a substrate.

10   In the processing of a substrate to fabricate electronic devices, such as electrical circuits and displays, etching processes are carried out to etch patterns in the substrate that correspond to layers or components of the electronic devices. For example, the patterns may comprise gates, vias, contact holes, or interconnect lines. Typically, a patterned mask of etch-resistant features comprising resist or hard-mask
15   materials is formed on the substrate, and exposed areas of the substrate between the etch-resistant features are etched to form the patterns.

During the etching process, an endpoint detection method is used to evaluate and control the progress of etching through the dielectric layer, such as to stop
20   or change the etching at a predetermined trench etch depth. In interferometric endpoint detection methods, as illustrated in Figure 1 (Prior Art), a light beam **76** is directed onto the substrate **10** and a reflected light beam **78** emerges from the substrate **10**. Constructive and destructive interference of portions of the reflected light beam **78** over time modulate the light beam **78** to form interference fringes, such as intensity maxima
25   and minima. The reflected light beam **78** is detected by a detector that generates an interference signal, which is monitored to determine an endpoint of the etching process. When the reflection signal exhibits fringes that arise from the interference between a primary reflection **50** from the surface of the substrate **10** and reflections from the first couple of layers, such as from mainly the second layer **22**. The interference fringes are
30   used to measure the etch rate, the etch depth, and determine whether an etching process endpoint has been reached.

However, a portion **76b** of the light beam **76** that is incident on the exposed areas **61** between the mask features **62** is partially transmitted to deep layers
35   **23** below the first and second layers **30, 22**, such as to third **23**, or fourth (not shown) layers. The portions of the light beam **51-53** reflected from these deep layers **23**

undesirably interferes with the primary reflection **50**, adding noisy, redundant interference fringes to the reflected light beam **78** that make the meaningful interferences fringes in the reflection signal more difficult to identify. Another light beam portion **76a** that is incident on the substrate **10** is reflected from the mask features **62**,

5   such as from the surface **17** of the mask **15** or even the layers **30, 22, 23** below the mask material. These extraneous reflections **40-44** also interfere with the reflected light beam **78** and add to the total reflection signal, decreasing the effective signal-to-noise ratio and possibly causing the indication of false endpoints.

10   As semiconductor devices are processed to be finer in scale, it is desirable to detect endpoint with higher precision and increased accuracy. The reflections **52, 53, 40-44** from the mask features **62** and deep layers **23** effectively limit the precision and accuracy of endpoint detection by adding noise to the reflection signal. This noise is sometimes removed using filters such as bandpass filters, which

15   increase the complexity of endpoint detection and often do not entirely remove the noise. In order to etch shallower trenches, and etch trenches to a more exact depth, it would be desirable to have an endpoint detector capable of a higher precision. In conventional interferometric endpoint detectors, the noise that is added to the reflection signal degrades the ability to detect endpoint. For example, some conventional

20   interferometric endpoint detectors have a minimum detectable depth of about 320 nm of a trench being etched.

          Thus, it is desirable to interferometrically detect the endpoint of a substrate processing step to a higher precision. It is also desirable to interferometrically

25   detect endpoint with less susceptibility to false endpoints, and thus improved accuracy.

SUMMARY

A method of etching a substrate comprises placing a substrate in a process zone. The substrate comprises a material having a thickness. An etchant gas

5   is introduced into the process zone. The etchant gas is energized to etch the material. An endpoint of etching the material is determined by (i) reflecting a light beam from the substrate, the light beam having a wavelength selected to have a coherence length in the substrate of from about 1.5 to about 4 times the thickness of the material, and (ii) detecting the reflected light beam to determine an endpoint of the substrate etching

10   process.

In another method of etching the substrate, the material of the substrate has exposed regions between features of a patterned mask. The endpoint of etching the material is determined by (i) reflecting a light beam from the substrate, the light

15   beam having a wavelength selected to maximize an absorption differential that is a difference between the absorption of the light beam in the patterned mask and the absorption of the light beam in the material, and (ii) detecting the reflected light beam to determine an endpoint of the substrate etching process.

20   An apparatus for etching a substrate comprises a chamber with a substrate support to hold the substrate. A gas distributor introduces an etchant gas into the chamber. A gas energizer energizes the etchant gas to etch the material of the substrate. A light beam source reflects a light beam from the substrate, and the light beam has a wavelength selected to have a coherence length in the substrate of from

25   about 1.5 to about 4 times the thickness of the material. A light detector detects the reflected light beam and generates a signal in response to a measured intensity of the reflected light beam. A controller evaluates the signal to determine an endpoint of the substrate etching process.

30   In another apparatus for etching the substrate the substrate comprises a material with exposed regions between features of a patterned mask. A light beam source reflects a light beam from the substrate, and the light beam has a wavelength selected to maximize an absorption differential that is a difference between the absorption of the light beam in the patterned mask and the absorption of the light beam in the material.

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DRAWINGS

These features, aspects, and advantages of the present invention will become better understood with regard to the following description, appended claims,

5   and accompanying drawings which illustrate examples of the invention. However, it is to be understood that each of the features can be used in the invention in general, not merely in the context of the particular drawings, and the invention includes any combination of these features, where:

10   Figure 1 (Prior Art) is a schematic sectional side view of a substrate upon which a conventional light beam is being directed, and from which the light beam is being reflected;

Figure 2 is a schematic sectional side view of a substrate upon which a

15   light beam according to the present invention is being directed, and from which the light beam is being reflected;

Figure 3 is a plot of an intensity signal over time corresponding to a reflected light beam having a wavelength of about 254 nm;

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Figure 4 is a plot of an intensity signal over time corresponding to a reflected light beam having a wavelength of less than about 220 nm;

Figure 5 is a plot showing a minimum etch depth achievable using a light

25   beam with a wavelength of about 254 nm, and a minimum etch depth achievable using a light beam with a wavelength of less than about 220 nm, both as functions of percentage of the exposed area between the mask features;

Figure 6 is a plot showing the absorption coefficients (α) of a mask and a

30   dielectric layer as functions of a wavelength (λ) of a light beam being directed thereon;

Figure 7 is a flowchart of process steps used to etch a material of a substrate, detect an etching endpoint, and stop the etching process or change process conditions;

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Figure 8 is a schematic sectional side view of a substrate processing apparatus and endpoint detection system according to the present invention; and

Figure 9 is a schematic diagram of a controller of the substrate processing apparatus of Figure 8.

DESCRIPTION

An endpoint detection system is useful in the fabrication of integrated circuits on substrates and is particularly useful in the etching of dielectric, semiconductor, or conductor materials on the substrate. Dielectric and semiconductor materials are often layered on one another and make it difficult, for example, to etch through a thick overlying dielectric material while still stopping the etching process without etching through a thin underlying semiconductor material. The dielectric materials may include, for example, low-k dielectrics; and the semiconductor materials may include, for example, polysilicon or silicon. However, the present invention can be used in other processes such as evaporation, and should not be limited to the examples provided herein.

The substrate **110** shown in Figure 2 is an exemplary illustrative embodiment of a substrate that may be etched using the present process, and is not intended to be limiting. The substrate **110** comprises a patterned mask **115**, such as a patterned mask **115** comprising photoresist and/or hard mask (typically silicon oxide or silicon nitride) features **162** that are formed by lithographic methods. Between the mask features **162** are exposed regions **161** of the underlying materials of the substrate **110** that are open for etching. In the etching of dielectric materials, the mask **115** typically comprises photoresist. At the exposed regions **161**, below the plane of the mask **115**, the substrate **110** also comprises a first material **130** to be etched and an underlying material **122** below the first material **130**. For example, the first material **130** may be a dielectric material such as a low-k dielectric. An exemplary underlying material **122** comprises a thin silicon dioxide material having a thickness of from about 10 to about 300 nanometers.

An example of an endpoint detection method for substrate etching according to the present invention will now be described in which the first material **130** is etched and the endpoint is detected with high accuracy and precision, thus avoiding undesirably etching or damaging the underlying material **122**. As illustrated in Figure 2, a light beam **176** having a selected wavelength is focused on the substrate **110** during the etching process and the intensity of the reflected light beam **178** is measured. The various reflections **150-153** of the light beam **176** constructively or destructively interfere

to produce a reflected light beam **178** with a rapidly modulating intensity as etching progresses, and the modulating intensity is monitored to indicate the endpoint.

In one version, the wavelength of the light beam **176** is selected to have a limited coherence length (d) in the substrate **110** to reduce noise in the intensity signal **210** of the reflected light beam **178**. While propagating through the substrate **110** within the coherence length (d), the light beam **176** maintains a defined phase such that the separately reflected portions **150, 151** of the light beam **176** within the coherence length can interfere with each other to create interference fringes. In Figure 2, the coherent light is shown by the solid and dashed lines.

However, as the initially coherent light beam **176** propagates through its path in the substrate **110**, the light beam **176** progressively loses its coherence because of self-interference of the light beam **176** as well as absorption and re-emission by the substrate material. After propagating farther than the coherence length, the light beam **176** becomes incoherent, as shown by the alternating dotted-dashed lines in Figure 2. The incoherent reflections **152, 153** do not substantially modulate the intensity of the entire reflected beam **178** over time. In other words, after a portion of the light beam **176** propagates in the substrate **110** beyond the coherence length, that portion of the light beam **176** loses its defined phase such that interference between reflected portions of the light beam **176** substantially does not occur. The coherence length (d) may be approximated by the following proportionality:

$$d \propto \frac{\lambda^2}{\Delta \lambda}$$

where λ is the wavelength whose coherence is being considered and $\Delta\lambda$ is the bandwidth of wavelengths of the light beam **176**. The wavelength λ of the light beam **176** in the first material **130** is inversely proportional to the refractive index of the first material **130**.

The wavelength selection may comprise a particular wavelength or a particular wavelength bandwidth to limit the coherence length in the substrate **110**. For example, to decrease the coherence length (d), a particular wavelength λ that is being detected may be chosen to be smaller in order to decrease the nominator λ^2 in the above equation. Alternatively, the wavelength bandwidth $\Delta\lambda$ in the denominator may be

increased to decrease the coherence length (d). Sometimes, the wavelength selection involves adjusting both the particular wavelengths λ used and the bandwidth of the wavelengths ($\Delta\lambda$). In one embodiment, a wavelength is selected such that the coherence length of the light beam **176** is from about 1.5 to about 4 times a thickness of the first material **130**, or even from about 2 to about 3 times the thickness of the first material **130**, as shown in Figure 2.

Additionally or alternatively, the wavelength of the light beam **176** may be selected such that a first portion **176a** of the light beam **176** that impinges on the features **162** of the mask **115** is substantially entirely absorbed in the mask **115**. If this first portion **176a** of light were reflected from the mask **115**, it would result in redundant interference fringes in the reflection signal that would obscure the endpoint from being accurately and precisely detected.

However, it is also important that a second portion **176b** of the light beam **176** be substantially transmitted back and forth through the first material **130**. The second portion **176b** of the incident light beam **176** enters exposed regions **161** of the substrate **110** that are being etched to generate an etch signal, and is partially reflected. The second portion **176b** of the ultraviolet light beam **176** passes through the first material **130** and reflects back from the substrate **110** with a beneficially increased ratio of intensity of reflection from the first material **130** to intensity of reflection from the mask **115**. A first fraction **151** of the second portion **176b** passes through the first material **130** and is reflected from the interface **126** between the first material **130** and a first underlying material **122**. A second fraction **152** of the second portion **176b** passes through the dielectric material **130** and the first underlying material **122**, and then is reflected from the interface **127** between the first underlying material **122** and a deep second underlying material **123**. A third fraction **153** of the second portion **176b** passes through the first material **130**, the first underlying material **122**, the deep second underlying material **123**, and then is reflected from the bottom **128** of the deep second underlying material **123**.

For example, the mask **115** may have a known absorption coefficient (α) that is the inverse of the depth of penetration of the light beam **176** into the first material **130**, the penetration depth at which the intensity of the light beam **176** has decreased by a factor of 1/e. The absorption coefficient is a function of wavelength, and can be

plotted as a curve, with local maxima that look like upward peaks in the curve representing optimal wavelengths at which to increase or decrease absorption. By considering this absorption coefficient, the thickness of the mask **115**, and the absorption coefficient of the first material **130**, the wavelength of the light beam **176** is

5   selected to maximize an absorption differential ($\Delta\alpha = \alpha_{mask} - \alpha_{first\ material}$) that is a difference between absorption of the light beam **176** in the mask **115** (α_{mask}) and absorption of the light beam **176** in the first material **130** ($\alpha_{first\ material}$). In one embodiment, the absorption coefficient of the mask **115** is selected such that the absorption length ($1/\alpha$) is less than about 1 micron. The light beam **176** is substantially absorbed by about a 1 micron

10 depth into a mask **115** that has a thickness of at least about 1 micron.

Figure 6 is a plot of absorption coefficient (α) as a function of wavelength (λ). As discussed above, the coherence length (d) of the light beam **176** is inversely proportional to its wavelength bandwidth ($\Delta\lambda$). In an optimal solution, the differential

15 ($\Delta\alpha$) between the absorption coefficient in the mask **115** and the absorption coefficient in the first material **130** is maximized under the constraints of a wavelength bandwidth ($\Delta\lambda$) that provides a desirable coherence length (d), such as from about 1.5 to about 4 times the thickness of the first material **130**, or even from about 2 to about 3 times this thickness.

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The reflectance or absorption of certain selected wavelengths in the mask **115** and the first material **130** may be determined early during the substrate processing, such as before the first stage of endpoint detection described above. For example, this calibration step may generate a reflectance or absorption "snapshot" for each substrate

25 **110** at the ultraviolet wavelengths of the light beam **176** used in determining the endpoint. A broadband spectrum of light, such as a broadband flash of light, is directed at the substrate **110**. Light that is reflected from the substrate **110** is detected to determine the absorption and reflection characteristics of that particular substrate **110**.

30 Figure 3 is a plot of relative intensity of the reflection signal as a function of time elapsed in seconds for a light beam **76** having a wavelength of about 254 nm. In this illustrative embodiment, the first material **30** is a low-k dielectric with an index of refraction (n) of about 1.47. The peak-to-peak distance in the interference signal is $d_{pp} = \lambda/(2n)$, where λ is the wavelength of the light beam **76** and n is the index of

35 refraction of the first material **30**. In this example, d_{pp} is calculated to be about 86.4 nm.

The light beam **76** is substantially unabsorbed by the mask **15**, and therefore undesirable reflections are present in the total reflected light beam **78**. Typically, the reflected light beam **78** is received and converted into an electronic signal, and signal processing is used to purge the contribution of the undesirable reflections from the

5   electronic signal. For example, the electronic signal may contain interference components that are due to shifting phase between a trench reflection **50** and mask reflections **44**. Additionally, if the mask **15** is being partially etched and thickness of the mask **15** is therefore decreasing, shifting phase may occur between a reflection **40** from the surface of the mask **15** and a reflection from beneath the mask **41-44** to contribute a

10   low-frequency interference component. A digital signal processor (DSP) can be used to perform signal processing to remove these undesirable interference components, but the signal processing consumes time during which the electronic signal cannot typically be monitored for the presence of indicators of an endpoint. Therefore, the minimum duration within which endpoint can be called is limited by both the time requirements of

15   the digital signal processor and the wavelength of the light beam **76**. In this example, the signal processing may take about 35 seconds to produce a "clean" electronic signal, and then about 13 seconds may elapse before an endpoint can be detected. This lag time sums to about 48 seconds, which corresponds to about 3200 Angstroms of etching. Therefore, the etch depth is lower limited to about 3200 Angstroms.

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In comparison with Figure 3, Figure 4 is a plot of relative intensity of the reflection signal as a function of time elapsed in seconds for a light beam **176** having a wavelength of less than about 220 nm. The material of the mask **115** is substantially absorbent to the light beam **176** at this wavelength, and therefore a higher signal-to-

25   noise ratio is obtained. With the higher signal to noise ratio, little or no signal processing may be needed. In the example illustrated, the signal processing takes about 20 seconds, and 12 seconds later the minimum endpoint can be called where the etching process has reached a desirably smaller etch depth of about 1800 Angstroms.

30   A comparison of the minimum trench depths at which endpoint can be identified, in a conventional longer wavelength endpoint detection system (diamond line, 254 nm wavelength) and a shorter wavelength endpoint detection system according to the present invention (triangle line, 215 nm wavelength), are illustrated in Figure 5. The plot shows minimum trench depth in angstroms (Å) as a function of exposed area as a

35   percentage of total area of the substrate **110**. As the exposed area increases,

reflections from the features **162** of the mask **115** diminish and both methods improve in precision. However, at typical percentages of exposed area the shorter wavelength demonstrates a marked improvement in precision over the longer wavelength. For example, for an exposed area of less than about 50%, the minimum detectable trench

5 depth using the 254 nm light beam is about 3100 Angstroms, which is equivalent to about 310 nm. In contrast, the minimum detectable trench depth using the 215 nm light beam is less than about 1900 Angstroms, which is equivalent to less than about 190 nm.

Thus, it is desirable to increase absorption of the light beam **176** in the

10 mask **115** while maintaining a low absorption of the light beam **176** in the first material **130**. The wavelength is preferably selected to be less than about 240 nm to improve absorption of the light beam **176** in the mask **115** while maintaining a low absorption of the light beam **176** in the first material **130**. For example, the wavelength may be selected to be less than about 240 nm, or even from about 150 to about 220 nm, to

15 optimize the respective absorptions of the light beam **176**. These wavelength selections also particularly improve signal-to-noise ratio by removing interference between the primary reflection **150** and undesirable reflections **153** from deep layers **123**. For example, these wavelengths may lie approximately in the center of the wavelength bandwidth in the light beam **176**.

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The etching and endpoint detection method of the present invention can significantly improve substrate yields by improving the precision of endpoint detection in the time dimension, thereby reducing etching or other damage of the layer **122, 123** underlying the dielectric layer **130**, such as when the underlying layer **122** is a thin gate

25 oxide layer during etching of a low-k dielectric layer **130**. For example, a minimum detectable trench depth of less than about 200 nm can often be achieved. Additionally, the minimum detectable exposed area **161** is reduced. By decreasing the coherence length of the light beam **176** in the substrate **110** and increasing absorption of the light beam **176** in the mask **115**, extraneous and noisy interference fringes are removed,

30 thus improving the accuracy of endpoint detection. By stopping the etching process before the underlying layer **122** is damaged by the aggressive etching process step, the present endpoint detection method provides higher yields and better quality of integrated circuits.

The endpoint is typically detected by counting a number of interference fringes in the intensity signal **210** of the reflected light beam **178**, the interference fringes being periodic points in the intensity signal **210**, such as local minima or maxima where the derivative of the intensity signal **210** is approximately zero. For example, the

5   endpoint may be detected by counting a sequence of maxima, or alternatively by counting a sequence of minima. Fractional fringes can be counted according to the estimated time until the next periodic point based on the shape of the signal waveform. The number of interference cycles in the modulation of the combined ultraviolet light beam **178** reflected from the substrate **110** is about $d(2n/\lambda_0)$, where n is the refractive

10   index of the first material **130**, d is the etch depth, and λ_0 is the vacuum wavelength of the light beam **176**. Once a predetermined number of interference fringes are counted, the etching endpoint is determined to have occurred or be near. Alternatively, the endpoint may be detected by comparing the reflection intensity signal **210** to an expected intensity pattern.

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In the process of etching and endpoint detection, as represented by the flowchart of Figure 7, the thickness of the first material **130** that is being etched is continuously measured. In one embodiment, etching proceeds to near completion, such as with about 300 Angstroms of the first material **130** remaining on the substrate

20   **110**, at which point the etching process is stopped, or alternatively at which point the first process conditions are changed to second process conditions to reduce the etch rate. The second process conditions provide a slower and thus more controlled etching of the first material **130**, and increase etching selectivity ratio to promote etching of the first material **130** relative to the underlying material **122**. The etch rate can be reduced

25   by changing the composition of the etchant gas, such as by removing aggressive gases, lowering RF bias power levels, lowering the substrate temperature, etc.

The endpoint detection method described herein can be used to detect the thickness of the material **130** and controllably change process conditions after a given thickness of the first material **130** is reached. In etching processes, the endpoint

30   detection method can be used to change the process gas composition to provide particular etch rates or etching selectivity ratios. The endpoint detection method may be used to detect the moment at which most of the first material **130** is etched so that the first process conditions can be changed to less aggressive or second process

35   conditions, or vice versa, to obtain the desired change in etch rate, etching selectivity

ratio, or a change in any other property of the etching process, for example, higher/lower etch rates or etching of an underlying layer **123** having a different composition. For example, the endpoint detection method can be used to stop the etching process after a first highly aggressive etching step, which provides high etch rates due to the presence of a fluorinated gas in the etchant gas, to determine the starting point for a second and less reactive etching step, which uses an etchant gas that is substantially absent the fluorinated gas to etch the remaining first material **130** at a slower etch rate to obtain more controlled etching.

The substrate **110** is etched in a substrate processing apparatus **240**, such as the embodiment schematically illustrated in Figure 8, available from Applied Materials Inc., Santa Clara, California. The apparatus **240** comprises a process chamber **242** having a process zone **244** for processing the substrate **110**, and a support **246** such as an electrostatic chuck that holds the substrate **110** in the process zone **244**. The ceiling of the process chamber **242** can be flat or rectangular shaped, arcuate, conical, dome-shaped, or multi-radius dome-shaped. Preferably, the ceiling is dome-shaped to provide a uniform distribution of plasma source power across the entire volume of the process zone **244** and to provide a more uniform plasma ion density across the substrate surface than a flat ceiling.

The substrate **110** is transferred by a robot arm (not shown) from a load-lock transfer chamber (not shown) through a slit valve (not shown) and placed into a process zone **244** of the chamber **242**. The substrate **110** is held on the support **246** by an electrostatic chuck and helium is supplied through apertures in the support **246** to control the temperature of the substrate **110**. Thereafter, the process conditions in the process chamber **242** are set to process the material **130** of the substrate **110**, the process conditions comprising one or more of process gas composition and flow rates, power levels of gas energizers, gas pressure, and substrate temperature. The process can also be performed in multiple stages, for example, each stage having different process conditions. For example, in an etching process, one or more compositions of process gas comprising etchant gas for etching the substrate **110** are introduced into the chamber **242** through the gas distributor. Suitable etchant gases for etching materials on the substrate **110** include, for example, chlorine-containing gases and fluorine-containing gases, such as fluorocarbons, and mixtures thereof. The chamber **242** is typically maintained at a pressure ranging from about 0.1 to about 400 mTorr.

The etchant gas composition is selected to provide high etch rates and/or high etching selectivity ratios for etching the overlying dielectric material **130** relative to the underlying layer **122**. When multiple layers are being sequentially etched, first, second, third, etchant gas compositions can be sequentially introduced into the chamber **242** to

5   etch each particular layer.

Process gases, such as the etchant gases described herein, are introduced into the process zone **244** of the chamber **242** through a gas distributor **248** that includes a process gas source and a gas flow control system that comprises a gas flow control

10   valve. The gas distributor **248** can comprise one or more gas outlets **250** located at or around the periphery of the substrate **110** (as shown), or a showerhead mounted on the ceiling of the chamber **242** with outlets therein (not shown). Spent process gas and etchant byproducts are exhausted from the process chamber **242** through an exhaust system **252** (typically including a roughing pump and a turbomolecular pump). A throttle

15   valve **254** is provided in the exhaust system **252** to control the flow of spent process gas and the pressure of process gas in the chamber **242**.

A plasma is generated from the process gas using a gas energizer **256** that energizes the process gas by coupling an electric field into the process zone **244** of

20   the chamber **242**, or into a remote zone adjacent to the process chamber **242**. The plasma in the process zone **244** is maintained at first process conditions suitable for etching the dielectric material **130** of the substrate **110**. A suitable gas energizer **256** comprises an inductor antenna **258** consisting of one or more inductor coils having a circular symmetry with a central axis coincident with the longitudinal vertical axis that

25   extends through the center of the chamber **242** and is perpendicular to a plane of the substrate **110**. When the inductor antenna **258** is positioned near the dome ceiling, the ceiling of the chamber **242** comprises dielectric material, such as aluminum oxide, which is transparent to RF fields and is also an electrical insulator material. The frequency of the RF voltage applied to the inductor antenna **258** is typically from about

30   50 kHz to about 60 MHz, and more typically about 13.56 MHz; and the RF power level applied to the antenna **258** is from about 100 to about 5000 Watts.

In addition to the inductor antenna **258**, one or more process electrodes **260, 262** can be used to accelerate or energize the plasma ions in the chamber **242**.

35   The process electrodes **260, 262** include a ceiling or sidewalls of the chamber **242** that

are electrically grounded or biased to serve as a first electrode **260** that capacitively couples with a second electrode **262** below the substrate **110**, to form a capacitive electric field that generates or energizes the plasma in the chamber **242**. Preferably, the first and second electrodes **260, 262** are electrically biased relative to one another

5   by the electrode voltage supply that includes an AC voltage supply for providing a plasma generating RF voltage to the second electrode **262** and a DC voltage supply for providing a chucking voltage to the electrode **260**. The AC voltage supply provides an RF generating voltage having one or more frequencies of from about 400 kHz to about 13.56 MHz at a power level of from about 50 to about 3000 Watts.

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The process chamber **242** further comprises an endpoint detection system **264** that operates according to the above-described endpoint detection method for detecting an endpoint of a process being performed in the chamber **242**. Generally, the endpoint detection system **264** comprises a light beam source **266** adapted to emit the

15   incident light beam **176**, and a light detector **270** that measures the intensity of the reflected light beam **178** from the substrate **110** to generate the reflected intensity signal **210**. A focusing assembly **268** may optionally be included for focusing the incident light beam **176**, onto the substrate **110**. A controller **300** counts the number of interference fringes in the reflected light beam signal. The controller **300** may additionally or

20   alternatively compare portions of the real-time measured reflection signal waveform to a stored characteristic waveform, or other representative pattern, and adjust process conditions in the process chamber **242** when the two waveforms have substantially the same shape.

25   The light source **266** comprises a monochromatic or polychromatic light source that generates an incident light beam **176** having an intensity sufficiently high to provide a reflected light beam **178** that is reflected from the substrate **110** with a measurable intensity. In one version, the light source **266** comprises the ambient plasma in the chamber **242**. In another version, the light source **266** comprises a

30   monochromatic light source that provides a selected wavelength of light, for example, a He-Ne or ND-YAG laser. In another version, the light source **266** provides polychromatic light, such as a xenon or Hg-Cd lamp. Optionally, the polychromatic light source **266** can be filtered to provide an incident light beam **176** having the selected wavelengths or color filters can be placed in front of the light detector **270** to filter out all

35   undesirable wavelengths except the desired wavelengths of light, prior to measuring the

intensity of the reflected light beam **178** entering the light detector **270**. For example, the filters can be used to filter out wavelengths that are not in the desired wavelength bandwidth (Δλ) discussed above in order to attain the desired coherence length of the light beam **176** in the substrate **110**. Typically, this light source **266** generates a

5   coherent, ultraviolet light beam **176**. For example, the light source **266** may be adapted to generate an emission spectrum of light in wavelengths of less than about 240 nm, such as from about 150 to about 220 nm.

One or more convex focusing lenses **274a**, **274b** are used to focus the

10   incident light beam **176** from the light source **266** as a beam spot **280** onto the substrate **110** and to focus the reflected light beam **178** back on the active surface of the light detector **270**. The size or area of the beam spot **280** should be sufficiently large to compensate for variations in surface topography of the substrate **110** to enable etching of high aspect ratio features having small openings, such as vias or deep and narrow

15   trenches. The area of the reflected light beam **178** should be sufficiently large to activate a large portion of the active light detecting surface of the light detector **270**. The incident and reflected light beams **176**, **178** are directed through a transparent window **282** in the process chamber **242** that allows the light beams **176**, **178** to pass in and out of the process zone **244**.

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Optionally, a light beam positioner **284** is used to move the incident light beam **176** across the substrate surface to locate a suitable portion of the dielectric material **130**, and optionally also a suitable portion of the mask **115**, on which to "park" the beam spot **280** to monitor the substrate processing. The light beam positioner **284**

25   comprises one or more primary mirrors **286** that rotate at small angles to deflect the light beam **176** from the light source **266** onto different positions of the substrate **110** (as shown). Additional secondary mirrors can be used (not shown) to intercept the reflected light beam **178** that is reflected from the substrate **110** and focus the light beam **178** on the light detector **270**. In another embodiment, the light beam positioner

30   **284** is used to scan the light beam **176** in a raster pattern across the substrate surface. In this version, the light beam positioner **284** comprises a scanning assembly consisting of a movable stage (not shown) upon which the light source **266**, focusing assembly **268**, collecting lens, and detector **270** are mounted. The movable stage can be moved through set intervals by a drive mechanism, such as a stepper motor, to move the beam

35   spot **280** across the substrate **110**.

The light detector **270** comprises a light sensitive electronic component, such as a photomultiplier, photovoltaic cell, photodiode, or phototransistor, which provides an electrical signal in response to a measured intensity of the reflected light beam **178** that is reflected from the substrate **110**. A signal filter (not shown) can be plated in front of the light detector **270**. The signal can be in the form of a change in the level of a current passing through an electrical component or a change in a voltage applied across an electrical component. The reflected light beam **178** undergoes constructive and/or destructive interference which increases or decreases the intensity of the light beam **178**, and the light detector **270** provides an electrical output signal in relation to the measured intensity of the reflected light beam **178**.

The electrical signal generated by the light detector **270** is passed to a controller **300** for evaluation. An illustrative block diagram of an embodiment of the controller **300** and associated computer-readable program **320** is shown in Figure 9. The controller **300** may comprise a plurality of interface cards including, for example, analog and digital input and output boards, interface boards, such as a hardware interface board **304**, and motor controller boards. The controller **300** further comprises a central processing unit (CPU) **306**, such as for example a 68040 microprocessor, commercially available from Synergy Microsystems, California, or a Pentium Processor commercially available from Intel Corporation, Santa Clara, California, that is coupled to a memory **308** and peripheral computer components, as shown in Figure 9. Preferably, the memory **308** includes a removable storage media **310**, such as for example a CD or floppy drive, a non-removable storage media **312**, such as for example a hard drive, and random access memory **314**. The interface between an operator and the controller **300** can be, for example, via a display **316** and a light pen **318**. The light pen **318** detects light emitted by the display **316** with a light sensor in the tip of the light pen **318**. To select a particular screen or function, the operator touches a designated area of a screen on the display **316** and pushes the button on the light pen **318**. Typically, the area touched changes color, or a new menu is displayed, confirming communication between the user and the controller **300**.

The computer-readable program **320** on the controller **300** calculates, in real time, the thickness of the dielectric material **130** remaining of the substrate **110** and accordingly adjusts the process conditions in the process chamber **242**. The computer program typically counts the number of interference fringes in the intensity signal **210** of

the reflected light beam **178** and, after a predetermined number of fringes are reached, alters process conditions in the chamber **242** according to programmed guidelines. The computer-readable program **320** can alternatively include program code to compare the shape of the reflection signal to a stored characteristic waveform, or other

5   representative pattern, and determine the endpoint of the etching process when the monitored reflection signal matches the stored characteristic waveform or pattern.

      The computer-readable program **320** may be stored in the memory **308**, for example, on the non-removable storage media **312** or on the removable storage media

10   **310**. The computer-readable program **320** generally comprises process control software comprising program code to operate the chamber **242** and its components, process monitoring software to monitor the processes being performed in the chamber **242** safety systems software, and other control software. The computer-readable program **320** may be written in any conventional computer-readable programming language, such as for

15   example, assembly language, C^{++}, Pascal, or Fortran. Suitable program code is entered into a single file, or multiple files, using a conventional text editor and stored or embodied in computer-usable medium of the memory **308**. If the entered code text is in a high level language, the code is compiled, and the resultant compiler code is then linked with an object code of precompiled library routines. To execute the linked, compiled object code,

20   the user invokes the object code, causing the CPU **306** to read and execute the code to perform the tasks identified in the program **320**.

      Figure 9 also shows an illustrative block diagram of a hierarchical control structure of a specific embodiment of the computer-readable program **320**. Using the

25   light pen interface **318**, a user may enter instructions into the computer-readable program **320** in response to menus or screens shown on the display **316**. The computer-readable program **320** includes program code to control the substrate position, gas flow, gas pressure, temperature, RF power levels, and other parameters of a particular process, as well as code to monitor the chamber process. The process sets

30   are predetermined groups of process parameters necessary to carry out specified processes. The process parameters are process conditions, including without limitations, gas composition, gas flow rates, temperature, pressure and gas energizer settings such as RF or microwave power levels.

The process sequencer instruction set **322** comprises program code to accept a chamber type and set of process parameters from the computer-readable program **320** and to control its operation. The sequencer program **322** initiates execution of the process set by passing the particular process parameters to a chamber

5   manager instruction set **324** that controls multiple processing tasks in the process chamber **242**. Typically, the chamber manager instruction set **324** includes a substrate positioning instruction set **326**, a gas flow control instruction set **328**, a gas pressure control instruction set **330**, a temperature control instruction set **332**, a gas energizer control instruction set **334**, and a process monitoring instruction set **336**. Typically, the

10   substrate positioning instruction set **326** comprises program code for controlling chamber components that are used to load the substrate **110** onto the support **246** and optionally, to lift the substrate **110** to a desired height in the chamber **242**. The gas flow control instruction set **328** comprises program code for controlling the flow rates of different constituents of the process gas. The gas flow control instruction set **328**

15   controls the open/close position of gas flow control valves (not seen) to obtain the desired gas flow rate. The gas pressure control instruction set **330** comprises program code for controlling the pressure in the chamber **242** by regulating the opening size of the throttle valve **254** in the exhaust system **252** of the chamber **242**. The gas energizer control instruction set **334** comprises program code for energizing a gas in the chamber

20   **242**. For example, the gas energizer control subroutine **334** may comprise code for setting the RF bias voltage power level applied to process electrodes in the chamber **242**. Optionally, a temperature control instruction set may be used to control the temperature of the chamber components such as sections of the support **246**.

25   The process monitoring instruction set **336** comprises code for monitoring a process in the chamber **242**. In one version, the process monitoring instruction set **336** comprises a light detection instruction set **337** to control the light detector **270**. For example, the light detection instruction set **337** may comprise code to set detection parameters of reflected light beam **178**, such as ranges of wavelengths, or may

30   comprise code to process a detected signal from the detection means. Additionally, the light detection instruction set **337** may comprise code which determines the endpoint of a process according to a parameter set input by the operator. For example, the detector **270** delivers a signal related to the intensity of the reflected light beam **178** to the controller **300**. The light detection instruction set **337** contained in the controller **300**

35   may process the reflection signal corresponding to the reflected light beam **178** as a function of time and wavelength. The endpoint of the chamber process may be determined by the light detection instruction set **337** once the intensity signal **210** has

reached, for example, a predetermined level for a certain preselected amount of time. A signal is given by the light detection instruction set **337** to a factory automation host computer **338** to halt the chamber process or change the process conditions once the process endpoint has been reached.

The data signals received by and/or evaluated by the controller **300** may be sent to the factory automation host computer **338**. The factory automation host computer **338** comprises a host software program **340** that evaluates data from several systems, platforms or chambers, and for batches of substrates **110** or over an extended period of time, to identify statistical process control parameters of (i) the processes conducted on the substrates **110** (ii) a property that may vary in a statistical relationship across a single substrate **110** or (iii) a property that may vary in a statistical relationship across a batch of substrates **110**. The host software program **340** may also use the data for ongoing in-situ process evaluations or for the control of other process parameters. A suitable host software program comprises a WORKSTREAM™ software program available from aforementioned Applied Materials. The factory automation host computer **338** may be further adapted to provide instruction signals to (i) remove particular substrates **110** from the processing sequence, for example, if a substrate property is inadequate or does not fall within a statistically determined range of values, or if a process parameter deviates from an acceptable range; (ii) end processing in a particular chamber **242**, or (iii) adjust process conditions upon a determination of an unsuitable property of the substrate **110** or process parameter. The factory automation host computer **338** may also provide the instruction signal at the beginning or end of processing of the substrate **110** in response to evaluation of the data by the host software program **340**.

The present invention is described with reference to certain preferred versions thereof; however, other versions are possible. For example, the endpoint detection method of the present invention can be used to detect endpoint in deposition, cleaning, or other etching processes, as would be apparent to one of ordinary skill. For example, the method can be applied, as would be apparent to one of ordinary skill in the art, to detect endpoint in sputtering etch chambers, cleaning chambers, or deposition chambers. Therefore, the spirit and scope of the appended claims should not be limited to the description of the preferred versions contained herein.